Quality Analysis in Phase Modulated Radio over Fiber in WDM/DWDM Network

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Quality Analysis in Phase Modulated Radio over Fiber in WDM/DWDM Network

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by

Satyajit Sahoo

(Roll Number: 711EC4048)

based on research carried out

under the supervision of

Prof. Santos Kumar Das

May, 2016

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Certificate of Examination

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We the below signed, after checking the dissertation mentioned above and the official record book of the student, hereby state our approval of the dissertation submitted in partial fulfillment of the requirements of the degree of Masters of Technology in Department of Electronics and Communication Engineeringat National Institute of Technology Rourkela. We are satisfied with the volume, quality, correctness, and originality of the work.

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Supervisor's Certificate

This is to certify that the work presented in the dissertation entitled *Quality Analysis in Phase Modulated Radio over Fiber in WDM/DWDM Network* submitted by *Satyajit Sahoo*, Roll Number 711EC4048, is a record of original research carried out by him under my supervision and guidance in partial fulfillment of the requirements of the degree of *Master of Technology* in *Electronics and communication Engineering*. Neither this thesis nor any part of it has been submitted earlier for any degree or diploma to any institute or university in India or abroad.

Santos Kumar Das

Dedication

To my Parents, Teachers and Supreme Lord Sri Krishna.

Satyajit Sahoo

Declaration of Originality

I, *Satyajit Sahoo*, Roll Number *711EC4048* hereby declare that this dissertation entitled *Quality Analysis in Phase Modulated Radio over Fiber in WDM/DWDM Network* presents my original work carried out as a postgraduate student of NIT Rourkela and, to the best of my knowledge, contains no material previously published or written by another person, nor any material presented by me for the award of any degree or diploma of NIT Rourkela or any other institution. Any contribution made to this research by others, with whom I have worked at NIT Rourkela or elsewhere, is explicitly acknowledged in the dissertation. Works of other authors cited in this dissertation have been duly acknowledged under the sections "Reference" . I have also submitted my original research records to the scrutiny committee for evaluation of my dissertation.

I am fully aware that in case of any non-compliance detected in future, the Senate of NIT Rourkela may withdraw the degree awarded to me on the basis of the present dissertation.

May 26, 2016
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Abstract

There has been increasing demand for connection setup with a higher quality of service (QoS) in WDM/DWDM networks, especially in fields like radio over fibers, where phase modulation affects the link quality. Hence to meet guaranteed QoS in a phase modulated link, the effects of phase modulation on link quality is very much needed. The link quality is termed as quality factor (Q-factor). The primary objective is to use effectively the connections available to optimize the computed number of connections and reduce the blocked connections but at the same time guarantying QoS as per client's need. The analysis has been done by taking care of routing and wavelength assignment (RWA) techniques. The performance analysis is presented in terms of blocking probability.

- This work includes detailed mathematical analysis of how phase modulation affects link Q-factor.
- Eight bands complimentary inner outer band, four bands complimentary inner outer band, and middle outer band wavelength assignment techniques are used for analysis.
- Blocking probability versus connection requests, blocking probability versus wavelengths assigned, connections accepted for a given source-destination pair were analyzed for different wavelength assignment techniques.

***Keywords*: *Phase Modulation*; *Physical layer impairments*; *Radio over fiber*; *Wavelength division multiplexing*; *Blocking probability*.**

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Chapter 1

Introduction

1.1 Introduction

WDM/DWDM networks have proven to be the best solution for providing increased throughput and the best Q-factors. Pure optical connections including switches are used thereby removing the need for O-E-O conversions. Ideally, the physical layer is considered to have no noise, signal delay or signal degradation elements. But in practicality physical layer consists of multiple impairments. These Physical layer impairments (PLI) are responsible for the deterioration of the connection. The link quality is mathematically termed as Q-factor. That can be due to many attributes including linear and non-linear PLIs. Linear impairments include chromatic dispersion, polarisation mode dispersion, amplifier spontaneous noise, in-band/out-band crosstalk, insertion loss, fibre concatenation, polarisation dependent loss, etc. Non-linear PLIs include self-phase modulation, cross phase modulation, four wave mixing, stimulated raman scattering, stimulated brillouin scattering, etc. Following this introduction, literature survey is presented in the next section. The succeeding section is motivation behind the work. The final section describes organization of the entire thesis.

1.2 Literature Survey

Many previous works have analyzed different considerations of impairments. Ramamurthy et al. [1] calculated bit-error rate (BER) with amplifier spontaneous emission (ASE) noise as impairments. C. Politi et al. [2] studied Q-factor as quality parameter for transmission with four wave mixing (FWM) and cross phase modulation (XPM) as impairments. I. Tomokos et al. [3] calculated Q-factor with ASE, FWM, and XPM as impairments. S. K. Das et al. [4] studied BER as QoT parameter with in-band crosstalk and FWM as impairments. Huang et al. [5] studied ASE noise and polarization mode dispersion (PMD) as impairments and optical signal to noise ratio as quality parameter for transmission. Similarly, N. Sengezer et al. [6] analyzed Q-factor as QoT with ASE, crosstalks and PMD as impairments in consideration.

Radio over fiber (RoF) is a developing innovation as far as dependability, coverage, and security is concerned. RoF advanced during an era when industry fell for the union of wired and wireless communication systems. RoF is an exceptionally encouraging system to upgrade the limit and data transfer capacity for wireless radio signals over long separation. Some of most emerging fields of applications of this technology are broadband wireless access networks, satellite communication, video distribution frameworks, versatile broadband administrations, vehicular correspondences, airplane terminals, shopping centres and so on. In future optical domain processing in RoF could also provide optical mm-wave frequency mixing for up/down conversion of digital subcarrier frequencies without optical-to-electrical (O/E) and electrical-to-optical (E/O) conversions [7]. The mixing setup mostly uses electro-optic modulators but faces degradation due to chromatic dispersion. Phase modulator and dispersive fiber system is used for optical microwave mixing. So, phase modulation even affects link quality in RoF WDM/DWDM networks.

1.3 Motivation

Phase modulation degrades link quality. Particularly in fields like RoF in WDM/DWDM networks which are rapidly growing technology, phase modulation plays a significant role in frequency mixing techniques. So as to meet up to the guaranteed QoS in a phase modulated link, the effects of phase modulation analysis on link Q-factor is very much needed. The motivation behind the work is to use efficiently the connections available to optimize the computed number of connections and reduce the blocked connections but at the same time guarantying QoS as per client's demand.

1.4 Organisation of the thesis

Following to the introduction in **chapter 1**, rest of this thesis is organized as follows:

Chapter 2: It includes overview of WDM/DWDM Networks. Various kinds of WDM networks are discussed, which includes overview on types of routing techniques and wavelength assignment algorithms. A helicopter view of different kinds of routing and wavelength assignment (RWA) techniques are given. Physical layer impairments in optical communication along with their constraints are also presented.

Chapter 3: It includes complete mathematical analysis of phase modulation as an impairment in optical WDM/DWDM networks. System model of this work is also presented which derives the bit-error probability and finally Q-factor.

Chapter 4: It includes analytical results and discussions of this work. It analyses accepted connections for a given connection request and blocking probability at different wavelengths and also with various load or requests using different WA techniques like middle outer band WA and four bands/ eight bands complimentary inner outer band WA.

Chapter 5: Finally, this thesis concludes in this chapter with discussions on scope of future research.

Chapter 2

Physical Layer Impairments in WDM/DWDM networks

2.1 Introduction

This section includes brief discussion on kinds of WDM/ DWDM networks. A concise and succinct view on routing and wavelength assignment techniques is presented, which includes a short overview of various routing techniques and wavelength assignment algorithms. A helicopter view of physical layer impairments and their types are discussed in this section. There are various constraints in physical layer impairments like wavelength continuity constraint, wavelength distinct constraint, etc are also presented herein.

2.2 WDM/DWDM Networks

Wavelength Division Multiplexing(WDM) is most exploding area of optical networking. It is the process through which multiple wavelengths simultaneously use the same optical fiber channel for transmission of information from a given source to destination. As given in Figure 2.1, the two prominent windows of optical communication, put together, provide 50 THz of communication bandwidth. With proper technologies, optical fibers have been manufactured which provide such large bandwidths for optical communication. Figure of a typical WDM optical network is given in Figure 2.2. WDM networks are extremely evolutionary, since they have many advantages like it allows wavelength reuse, has increased capacity for same optical fiber, is reliable, scalable and provides higher QoS.

There can be various kinds of WDM networks like coarse WDM also known as CWDM and dense WDM networks which is also DWDM. The various parameters of WDM, CWDM and DWDM are given in Figure 2.3.

There can be other categorizations of WDM networks. They can be:

Broadcast-and-select networks: It is typically a small network with small number of nodes. Typically, it can support both broadcast and unicast communication. In broadcast

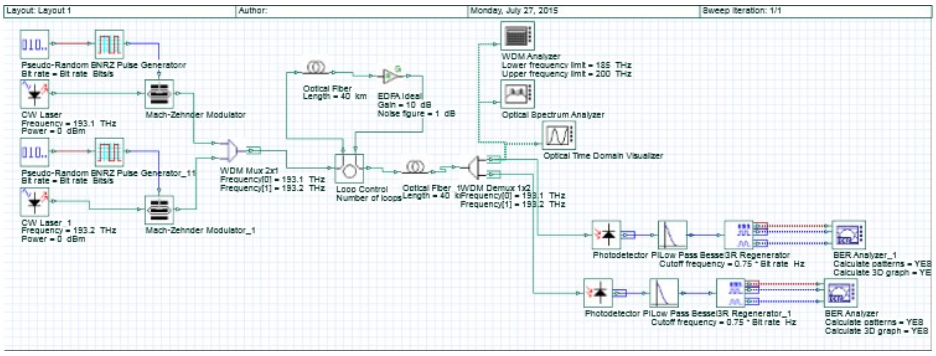


Figure 2.1: A Typical 2 channel WDM optical network simulated in Optisystem

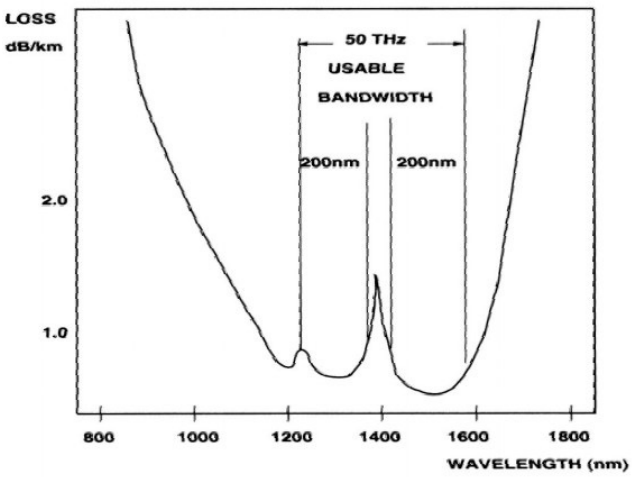


Figure 2.2: Usable bandwidth for optical communication

SPECIFICATIONS	WDM	CWDM	DWDM
CHANNEL SPACING	1310nm & 1550nm	Large,1.6nm-25nm	Small,1.6nm or less
NO OF BASE BANDS USED	C(1521-1560 nm)	S (1480-1520 nm), C(1521-1560nm), L(1561-1620 nm)	C (1521-1560 nm), L(1561-1620 nm)
COST PER CHANNEL	Low	Low	High
CHANNELS DELIVERED	2	17-18 at most	64,128 or even more
BEST APPLICATION	Passive Optical Networks	Short haul, Metro	Long Haul

Figure 2.3: Types of WDM Optical Networks

communication the signal is broadcast to all end nodes.

Wavelength routed networks: In such networks, the optical signal follows specific path unlike broadcast and select networks. The wavelength and the fiber material used by it, determines the future path of the signal. It communicates through lightpaths and all routing is done in optical domain.

The optical network traffic can be static or dynamic. In a static traffic, static establishment of lightpaths is done to meet connection demands. A set of lightpath demands are provided for certain time period during which respective lightpaths are established. For dynamic traffic, lightpaths are established on demand depending on current state of the network and resources that are available, such that resources are used efficiently. Here dynamic RWA or dynamic establishment of lightpaths is done. Owing to their efficiency, dynamic or on demand wavelength routed networks are mostly preferred over static networks.

2.3 Routing and Wavelength Assignment

Routing and Wavelength Assignment is the optical practice of allocating a connection to a link request and then allocating a light path with particular wavelength [8, 9]. The goal of RWA algorithm to achieve maximum connections within physical constraints. Since, RWA is a NP Complete problem and hence approached by these two steps: First, using a routing technique, a connection between a given source and destination is found and then second, an available wavelength is assigned for the selected route using wavelength assignment algorithms.

2.3.1 Routing Technique

Fixed Routing (FR): In fixed routing a fixed route or light path is allotted for a given connection to be established [10]. It is a very simple technique and is computed before in an offline manner and is not used in online or dynamic requests. Since routes for given source destination pair is fixed beforehand, so if a given request doesn't have the fixed allotted lightpath free, then the request gets blocked. So this technique faces high blocking probability owing to its simple algorithm. A typical FR optical network topology is given in Figure 2.4.

Fixed Alternate Routing (FAR): In this routing technique, a number of alternate light paths are allotted for a given pair of source and destination. The allotment here is also done in offline manner [11, 12]. Unlike fixed routing, FAR allocates many routes

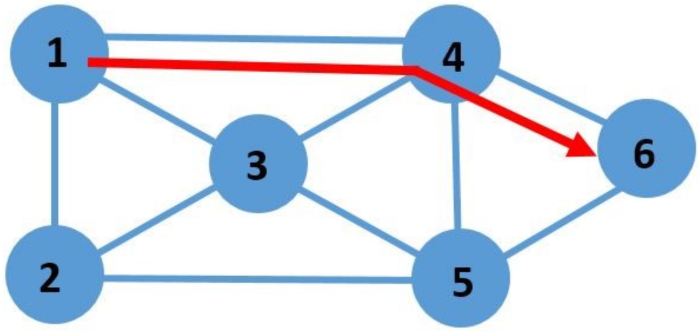


Figure 2.4: A Typical Fixed Routing Optical Network

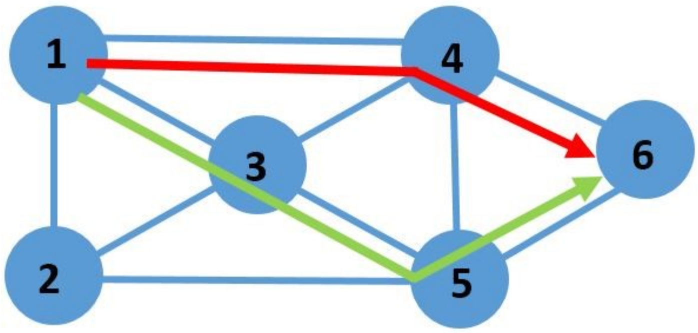


Figure 2.5: A Typical Fixed Alternate Routing Optical Network

instead of a single fixed lightpath. These lightpaths are allotted following some priority criteria. Generally, shortest path has highest precedence. Sometimes, for precedency, number of nodes that the given route crosses, is also a criterion that is considered. When a connection request comes, source node searches for a lightpath till the destination. If it finds no such connection available, then the connection request is blocked. Since, it provides more lightpaths for a given pair of nodes, so it has lower blocking probability than FR technique.A typical FAR optical network topology is given in Figure 2.5.

Adaptive Routing (AR): None of above techniques namely FR and FAR, consider current network state. So, they fail to allot routes online to the connection request. So, they have poor efficiencies. If precomputed paths are not available, the connection requests were blocked. But adaptive routing algorithm allots connection online i.e. dynamically depending on current state of the network and resources that are available [13]. When a demand for connection comes, all the possible connections are computed and the one with shortest or with highest priority is accepted. If there are more than one connection available with same priority say same path length, then any one of them is randomly chosen. The request is blocked if there are no paths available. This algorithm has least blocking probability than FR and FAR. AR is also quality aware, hence most efficient. Owing to its efficiency, we use adaptive routing in this work.A typical AR optical network topology is given in Figure 2.6.

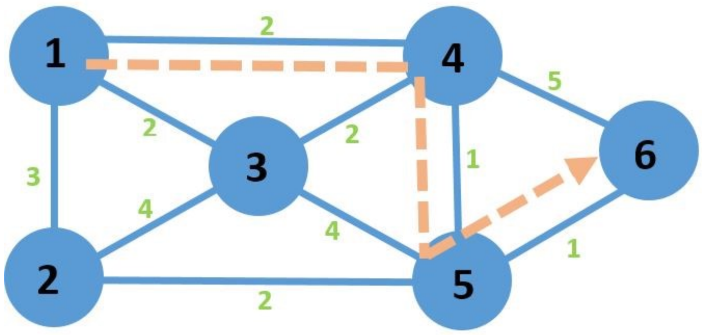


Figure 2.6: A Typical Adaptive Routing Optical Network

2.3.2 Wavelength Assignment Algorithm

Once the route is chosen, wavelength assignment(WA) technique allots a wavelength for the link.
The Routing and wavelength assignment problem has many restrictions like wavelength distinct constraint, wavelength continuity constraint, traffic engineering constraint and physical layer impairments constraint.

Wavelength Continuity Constraint (WCC): In absence of wavelength converters, an optical network faces this constraint. According to this constraint, a lightpath should be wavelength continuous. Throughout the connection the lightpath should have same wavelength. The lightpath is blocked if the particular wavelength is not available in any of the links. Equivalent to circuit switched networks there are optical networks that have wavelength converters whereas wavelength continuous networks lack them. Wavelength converters reduces blocking probability [14]. So, wavelength continuous networks have high rate of request blocking or blocking probability than circuit switched networks.WCC is explained in Figure 2.7.

Wavelength Distinct Constraint (WDC): Wavelength distinct constraint permits no two lightpaths to have same wavelength in any particular link. It is also known as wavelength clash constraint. Every wavelength is assigned to a particular lightpath and hence cannot be used by any other lightpath. So, there is a need for wavelength conversion for a lightpath to continue, if it's wavelength in previous link has already been assigned in the next link to some other lightpath. WCC is explained in Figure 2.8.

Physical Layer Impairment Constraint (PLIC): Physical layer in optical networks has many impairments like linear and non-linear, that degrade the connection quality. This constraint restricts the wavelength or connection selection so as to get certain level of

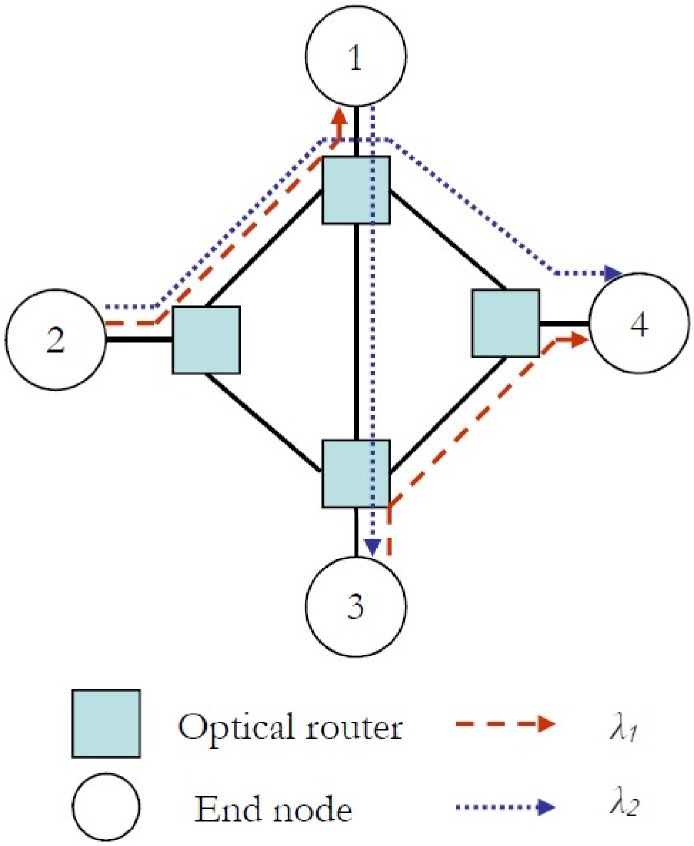


Figure 2.7: Wavelength Continuity Constraint

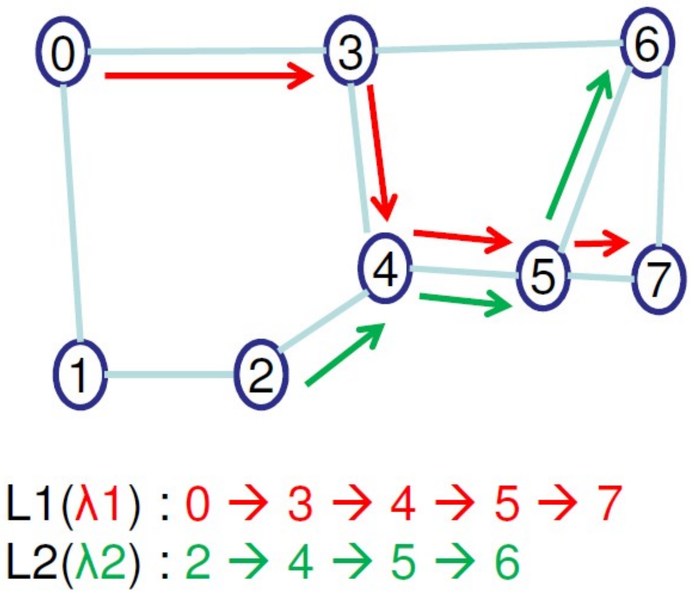


Figure 2.8: Wavelength Distinct Constraint

desired QoS.

Traffic engineering constraints (TECs): Traffic engineering constraint restricts connection or wavelength selection so as to get efficient resource utilization and reduce blocking probability.

There are various techniques for WA and they adopt any of the above constraints depending upon network architecture.

Random WA: Random WA allocates wavelengths randomly to a given connection request from the list of available wavelengths. Typically, numbers are assigned randomly using some particular seed value.

First-Fit WA (FFWA): In this scheme, at first all the wavelengths are listed in an increasing order to form a wavelength matrix. The higher precedency wavelength is allotted lower number. The lowest numbered wavelength i.e. highest priority wavelength is assigned to first connection request. FFWA has lower computational cost owing to ordered wavelength matrix and systematic WA. There is no need for searching for a wavelength. It also has lower blocking probability [15].

2.4 Physical layer Impairments (PLIs) in optical networks

Ideally Physical layer is considered having no noise, signal delay or signal degradation elements. But in practicality physical layer consists of so many impairments. These Physical Layer Impairments (PLIs) are responsible for the degradation of the connection QoS/QoT. Physical layer impairments in WDM/DWDM networks can be broadly of two kinds [16–18]. One is Linear impairments (LIs) which are static in quality and other is nonlinear impairments (NLIs) which are dynamic in characteristics. NLIs signal power dependent, whereas LIs are free from signal power . LIs affect each connection individually, whereas NLIs affects the individual connection and leads to interconnection noises. That is why in AONs, new connection allotment affects current connections. LIs are caused due to chromatic dispersion, effect of high range dispersion, PMD, etc. Linear scattering like Rayleigh scattering and Mie scattering also cause signal quality degradation. Linear scattering transfers some or all power from one mode transferred linearly to other leaky mode causing attenuation of transmitted light. It doesn't affect frequency of signal scattered. Similarly, nonlinear scattering losses like Stimulated Brillouin scattering (SBS) and Stimulated Raman Scattering (SRS) causes power from one mode to be carried over to same or other mode in both forward and backward direction but at a different frequency.

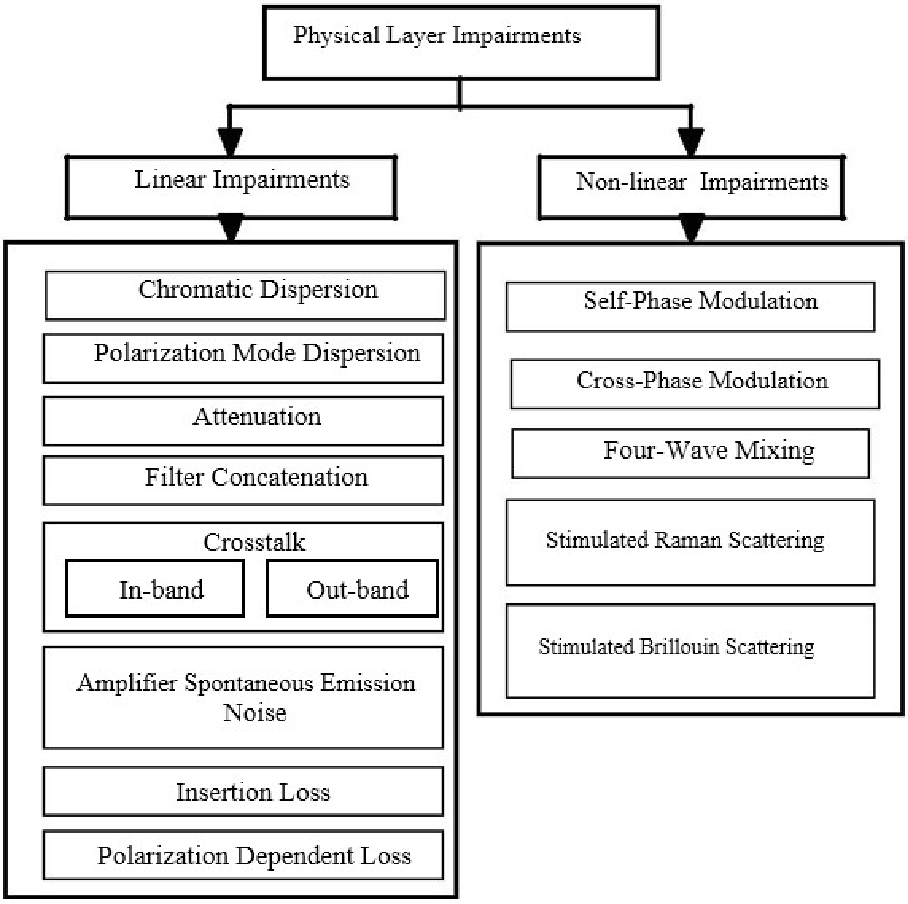


Figure 2.9: Kinds of PLIs in Optical networks

This kind of scattering gives gain but with some frequency shift. Brief classification of PLIs is given in Figure 2.9. These impairments can be summarized as follows:

Chromatic Dispersion (CD): When light pulse is transmitted through an optical fiber, it spreads due to chromatic dispersion impairment. It is also known as intermodal dispersion and occurs in all kinds of optical fiber owing to finite spectral linewidth of optical source.Since different spectral components of the optical light pulse travel at different speeds in an optical medium due to varying optical refractive index leading to varying propagation delay, pulse width spreads and leads to inter symbol interferences. It limits achievable data rate in high speed networks. Total dispersion caused due to CD is sum of dispersion caused due to each single fiber link.

Polarization Mode Dispersion (PMD): It is also a cause of pulse broadening and is also becomes cause of limiting factor for high data rate optical communication. It is random in nature and is due to both intrinsic and extrinsic factors that appear when fiber is actually manufactured. High fiber birefringence breaks circular geometry of fiber core and residual stress near glass core area are intrinsic factors, whereas stress due to mechanical bending and twisting of optical fiber are extrinsic reasons. These extrinsic and intrinsic factors lead to different polarization states causing varying group velocities, leading to broadening of pulse in frequency domain.

Amplifier Spontaneous Emission (ASE) Noise: It is a type of noise that is produced when spontaneously emitted radiation is amplified in a gain medium like optical amplifiers utilized at the routers, repeaters and preamplifier. It depends on how much more the noise PSD of the output in comparison to input noise PSD. This kind of noise is produced in both onward and rearward direction but onward direction propagated noise is cause of degradation of overall throughput of the system. Whereas backward propagating noise restricts the amplifier gain and increases noise in signal. This kind of noise can be subdued by enhancing laser intensiveness. This is expressed in decibels.

Polarization Dependent Loss (PDL): Owing to abnormality in the optical fiber, the two polarization components face dissimilar loss rates leaving wavering in optical SNR and errant and irregular signal quality degradation. It primarily occurs in optical components with passive characteristics.

Linear Crosstalk (LC): Optical switches and add-drop multiplexers are not ideal and in reality affect signal and connection quality, thereby causing component cross talk, which is also a PLI. Component crosstalk can be optical in band or optical out-of-band, in types depending on location of its spectrum in comparison to passband of the optical filter [19, 20]. Out-of-band crosstalk occurs because of channels of varying wavelengths and they are not that harmful since they can be tolerated by supressing them using narrow band optical filter whereas in band optical crosstalk are difficult to handle. They cause degradation of receiver system since here signal and interferer have wavelengths which are close in nature causing them to be in passband of optical filter. This kind of cross talk can also be homodyne or heterodyne. Figure 2.10 depicts signal with inband crosstalk.

Normally optical signals do not interact with material transmitting medium but when they occur, such processes are called nonlinear effects. They are so called because their amplitude depends on square of optical intensity. Depending on lower or higher optical powers, these effects become fainter or heftier. In spite of its lower value, it accumulates to large value as signal passes through longer distances through single mode fibers. In WDM systems, many channels are packed together in single fiber, so the nonlinear effects add up to higher values. This kind of effects are generically of two kinds: scattering and Kerr effects. Intensity dependent refractive index (RI) variation causes nonlinear impairments known as Kerr effects. Kerr effects include Self Phase Modulation(SPM), Cross Phase Modulation(XPM) and Four Wave Mixing (FWM). Whereas scatterings include Stimulated

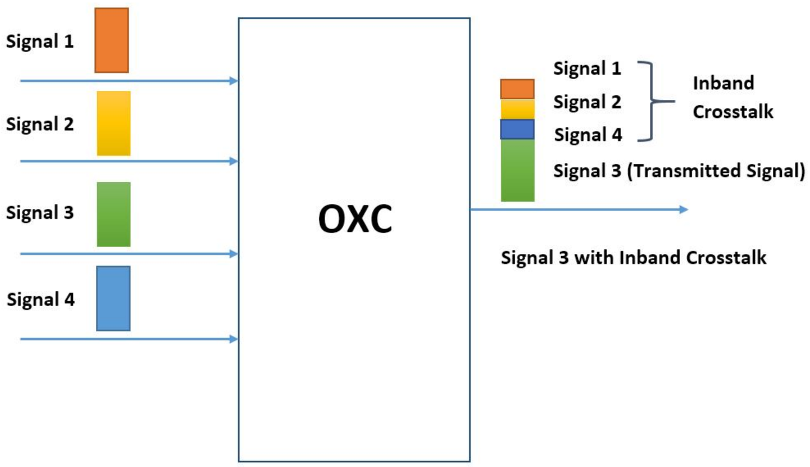


Figure 2.10: Illustration of crosstalk in an optical network

Brillouin Scattering (SBS) and Stimulated Raman Scattering (SRS). Summary of nonlinear impairments are discussed below.

Self-Phase Modulation (SPM): It is one of the Kerr effects. Intensity subjected refractive index leads to intensity subjected phase shift. So, nonlinear effects cause different transmission phases for peak and pulse edges ahead and behind. This effect due to Kerr effects is known as SPM. SPM can modify and widen frequency spectrum of optical pulse since time altering phase creates time altering frequency. It is used for frequency or wavelength switching and chiefly used for pulse compaction within single mode fiber optical signal communication.

Cross-Phase Modulation (XPM): It is also a result of Kerr effects. It is alike SPM excluding that overlapping but distinct pulses are considered. The alteration of RI of the fiber due to intensity wavering of one pulse results in phase modulation of the lapping pulse(s). Like in SPM, this phase modulation transforms into frequency modulation which results in pulse spectrum broadening. Intensity of XPM enhances when number of channels is raised or channel spacing is reduced. Overall strength of XPM is twice that of SPM.

Four-Wave Mixing (FWM): When three frequencies meet in a nonlinear optical medium, the photons of these three frequencies interact to produce a fourth photon. Thus a fourth frequency signal is produced because of interaction of other three frequencies which is an inter modulation effect which is known as four wave mixing (FWM). In dense WDMs because of reduction in channel spacing of wavelengths, the effect of FWM is intensified. Similar effect is seen for higher signal power levels. By reducing matching of phases, coherence of signals is reduced, thereby reducing effects of FWM.

Stimulated Brillouin Scattering (SBS): Due to thermal molecular vibrations within the optical fiber an approaching photon is scattered into an acoustic phonon and a scattered photon. This leads to signal modulation and is most prevalent nonlinear scattering loss since it appears at lower optical power unlike SRS. Frequency shift is mainly in backward direction and has no such shift in forward direction. The scattered light comes along as lower and upper sidebands. It restricts the limit of highest power that can be injected into an fiber. It is prevalent beyond a threshold power density like SRS. Unlike SRS, it appears at lower optical power.

Stimulated Raman Scattering (SRS): During the process of scattering an optical phonon is produced in SRS unlike an acoustic phonon produced in SBS. This is main difference between them. SRS appears at a higher power than SBS. It can appear in onward and rearward direction simultaneously. SRS scattering threshold power can be thousand times higher than that of SBS for a particular fiber. Both SRS and SBS affect throughput of system. SRS can be subdued using proper filtering techniques.

Chapter 3

Phase modulated WDM/DWDM Networks

3.1 Introduction

In this work impairments based on phase modulation is done. A system model for the same is given in the next section. In order to analyze effects of phase modulation impairment on link quality, a system model is proposed. Extensive mathematical analysis and derivation is done.

3.2 System model

In this work, impairments based on phase modulation is considered. A microwave signal with continuous wave directly modulates a laser diode with a wavelength of 1500 nm at a frequency of f_{RF}. At the yield of the laser diode, direct modulation causes frequency and intensity Modulation simultaneously. The waveform from the laser diode is added into a phase modulator obsessed with an electrical signal with a frequency of f_{LO} which has continuous waveform. A dispersive single mode fiber gets the signal at the output of the phase modulator as input but with a 17 ps/(nm.km) dispersion coefficient. The signal is detected by a photodetector with a bandwidth of 20-GHz at the output of the optical fibre link. Block diagram of phase modulation in optical network is as shown in Fig.1 with laser diode (LD) at frequency f_{RF} , phase modulator (PM) at frequency f_{LO}, single mode fibre (SMF) and photo diode (PD).

The optical field, $E_{LD}(t)$ at the output of Laser diode can be written as [7],

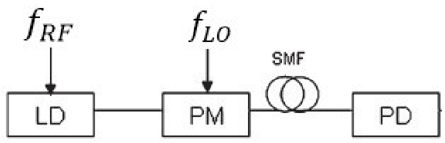


Figure 3.1: Phase modulation in optical Network

$$E_{LD}(t) = \sqrt{1 + mcos(2\pi f_{RF}t)}e^{j\beta sin(2\pi f_{RF}t)}e^{j2\pi f_0 t} \tag{3.1}$$

where, m is the intensity modulation index, β is the frequency modulation index at frequency f_{RF}, and f_0 is the frequency of the carrier.

LD characteristics in the linear portion of equation 3.1 can be estimated as,

$$E_{LD}(t) = (1 + \frac{m}{2}cos(2\pi f_{RF}t))e^{j\beta sin(2\pi f_{RF}t)}e^{j2\pi f_0 t} \tag{3.2}$$

Light of the output laser diode is mixed with the phase modulator. So optical field strength at the phase modulator output, $E_{PM}(t)$ is expressed as,

$$E_{PM}(t) = E_{LD}(t)e^{j\frac{\pi V}{V_\pi}cos(2\pi f_{LO}t)} \tag{3.3}$$

Where V is voltage at frequency f_{LO} applied to the phase modulator and V_π is the half-wave voltage of the modulator.

Simplifying equation 3.2 and 3.3, using Jacobi-Anger Expansions,

$$cos(zcos(\Theta)) = J_0(z) + 2\sum_{l=1}^{\infty}(-1)^l(J_{2l}(z)cos(2l\theta)) \tag{3.4}$$

$$sin(zcos(\Theta)) = -2\sum_{l=1}^{\infty}(-1)^l(J_{2l-1}(z)cos((2l-1)\theta)) \tag{3.5}$$

$$cos(zsin(\Theta)) = J_0(z) + 2\sum_{l=1}^{\infty}(J_{2l}(z)cos(2l\theta)) \tag{3.6}$$

$$sin(zsin(\Theta)) = 2\sum_{l=1}^{\infty}(J_{2l-1}(z)sin((2l-1)\theta)) \tag{3.7}$$

we get,

$$E_{PM}(t) = \sqrt{1 + mcos(2\pi f_{RF}t)}e^{j\beta sin(2\pi f_{RF}t)}e^{j2\pi f_0 t}e^{j\frac{\pi V}{V_\pi}cos(2\pi f_{LO}t)} \tag{3.8}$$

On further simplification,

$$E_{LD}(t) = (1 + \frac{m}{2}cos(2\pi f_{RF}t))e^{j2\pi f_0 t}$$

$$\times[J_0(\beta) + 2\sum_{k=1}^{\infty}(J_{2k}(\beta)cos(2\pi 2kf_{RF}t)) + 2j\sum_{k=0}^{\infty}(J_{2k+1(\beta)}sin(2\pi(2k+1)f_{RF}t))]$$

$$\times[J_0(\frac{\pi V_{LO}}{V_\pi}) + 2\sum_{k=1}^{\infty}(-1)^k(J_{2k}(\frac{\pi V_{LO}}{V_\pi})cos(2\pi 2kf_{LO}t))$$

$$+2j\sum_{k=0}^{\infty}(-1)^k(J_{2k+1}(\frac{\pi V_{LO}}{V_\pi})sin(2\pi(2k+1)f_{LO}t))] \tag{3.9}$$

Helpful articulations of complex envelopes of the spectral lines SL_f at the optical recurrence *f* can be obtained from equation 3.9,

$$SL_{f_0} = J_0(\beta)J_0(\frac{\pi V_{LO}}{V_\pi}) \tag{3.10}$$

$$SL_{f_0+\varepsilon(f_{RF}+f_{LO})} = \varepsilon jJ_1(\beta)J_1(\frac{\pi V_{LO}}{V_\pi}) + j\frac{m}{4}J_0(\beta)J_1(\frac{\pi V_{LO}}{V_\pi}) \tag{3.11}$$

$$SL_{f_0+\varepsilon f_{RF}} = \varepsilon J_1(\beta)J_0(\frac{\pi V_{LO}}{V_\pi}) + \frac{m}{4}J_0(\beta)J_0(\frac{\pi V_{LO}}{V_\pi}) \tag{3.12}$$

$$SL_{f_0+\varepsilon f_{LO}} = jJ_0(\beta)J_1(\frac{\pi V_{LO}}{V_\pi}) \tag{3.13}$$

with $\varepsilon = \pm 1$.

The regular beatings of $SL_{f_0+f_{LO}}$, with SL_{f_0} (noted $SL_{f_0} \times SL_{f_0+f_{LO}}$) and $SL_{f_0} \times SL_{f_0-f_{LO}}$ create the yield force of the stage modulator at a recurrence of f_{LO}. Both beating terms have the same abundancy however are out of stage seen in equation 3.10to 3.13. It provides no detected power at the output at f_{LO}.

The yield power of the phase modulator at recurrence of f_{RF} results from the prevailing beating terms $SL_{f_0+f_{RF}} \times SL_{f_0}$ and $SL_{f_0} \times SL_{f_0-f_{RF}}$. This time, both beating terms do not counteract each other because of the nearness of IM at the LD yield. As a result, power at

f_{RF} can be detected with the output power expressed as,

$$P(f_{RF}) = \eta m^2 {J_0}^2(\beta) {J_0}^2(\frac{\pi V_{LO}}{V_\pi}) \tag{3.14}$$

where η is photo diode responsivity, V_{LO} is voltage at the given frequency f_{LO}, and V_π is the half wave voltage for the modulator.

3.3 Q- Factor calculations due to phase modulation

The bit error probability for phase modulation, $P_{be}(PM)$ is expressed as [4],

$$P_{be}(PM) = 0.5erfc(SNR_{PM}) \tag{3.15}$$

Where signal to noise ratio due to phase modulation, SNR_{PM} can be as [21],

$$SNR_{PM} = \rho_s = \frac{P_r}{S_{ns}\beta_d} \tag{3.16}$$

where P_r is the received signal power, S_{ns} is the spectral density, β_d is the bandwidth of single polarization.

The received power P_r, can be expressed as,

$$P_r = \eta m^2 {J_0}^2(\beta) {J_0}^2(\frac{\pi V_{LO}}{V_\pi}) \tag{3.17}$$

Bandwidth, β_d can be expressed as [5],

$$\beta_d = \frac{\sigma}{(D_{PMD} \times \sqrt{L})} \tag{3.18}$$

where δ is the pulse broadening factor, D_{PMD} is the fiber PMD parameter, and L is the length of the link.

Now, $P_{be}(PM)$ can be expressed as,

$$P_{be}(PM) = 0.5erfc(\frac{\eta m^2 {J_0}^2(\beta) {J_0}^2(\frac{\pi V_{LO}}{V_\pi})}{S_{ns} \times \frac{\sigma}{(D_{PMD} \times \sqrt{L})}}) \tag{3.19}$$

Now, the Q-Factor due to phase modulation, $Q - Factor_{PM}$, can be expressed as,

$$Q - Factor_{PM} = \frac{1}{P_{be}(PM)} \tag{3.20}$$

Equation 3.20 is valid because $P_{be}(PM)$ and $Q - Factor_{PM}$ are inversely proportional.

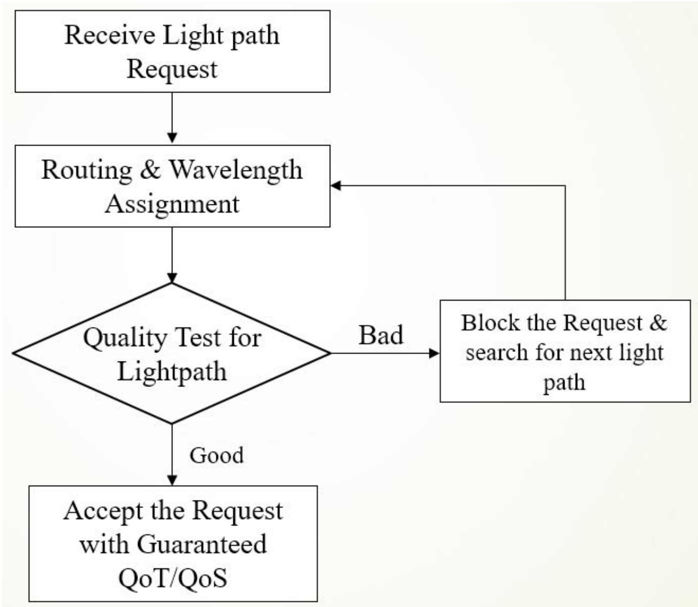


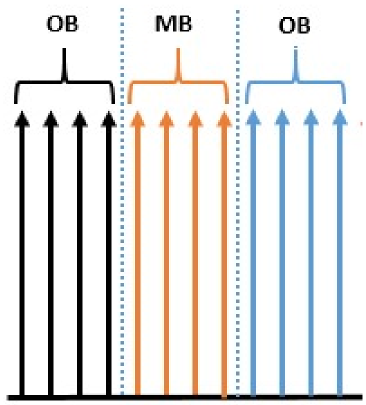
Figure 3.2: Flow chart of general quality aware routing and wavelength assignment

3.4 Algorithm and Flow chart

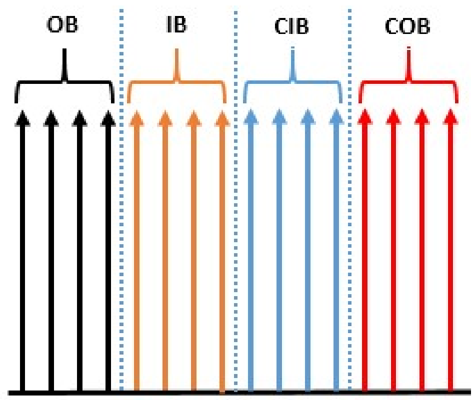
It shows the sequence of algorithms and flow charts used to analyse the accepted connection requests and blocking probability with respect to the number of wavelengths used and connections requested.

Generally, in RWA with guaranteed QoS, lightpath request is considered first. Then depending on routing technique and wavelength assignment (WA) technique used, lightpath is assigned. But to get the guaranteed QoS, the assigned lightpath undergoes the quality test. The quality test can be anything depending on client demands like BER, Q-factor, etc. If the lightpath passes the quality test then it is accepted, else the next available lightpath is checked. If no connections are available, then the connection request is blocked. The corresponding flow chart is represented in Figure 3.2. Here quality factor is driven by phase modulation as mentioned in equation 3.20.

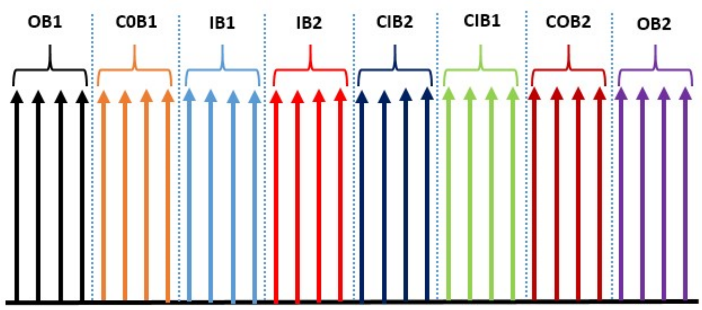
For wavelength assignment, four bands/ eight bands complimentary inner outer band wavelength assignment (CIOBWA) is implemented where transmission window is divided into four bands or eight bands respectively. In four bands CIOBWA, as proposed by S. K. Das et al. in [4],the transmission window is divided into 4 bands, namely, the inner and outer bands (IB and OB) and their complimentary bands (CIB and COB). Here CIB and IB are used for lower distant connections whereas COB and OB are used for longer distant connections. Eight bands CIOBWA is similar to that proposed by S. K. Mahapatra et al. in [22]. In this WA technique, transmission window is divided into eight bands with two of each IB, CIB, OB, and COB. Adhya et al. [23] proposed middle outer band random wavelength assignment technique (MOBRWA). It consists of three bands namely middle band and two outer bands and wavelength which was assigned randomly to the bands of the transmission window. Transmission windows for all these WA techniques are presented in Figure 3.3.



(a) Conventional MOBWA technique



(b) Four bands CIOBWA technique



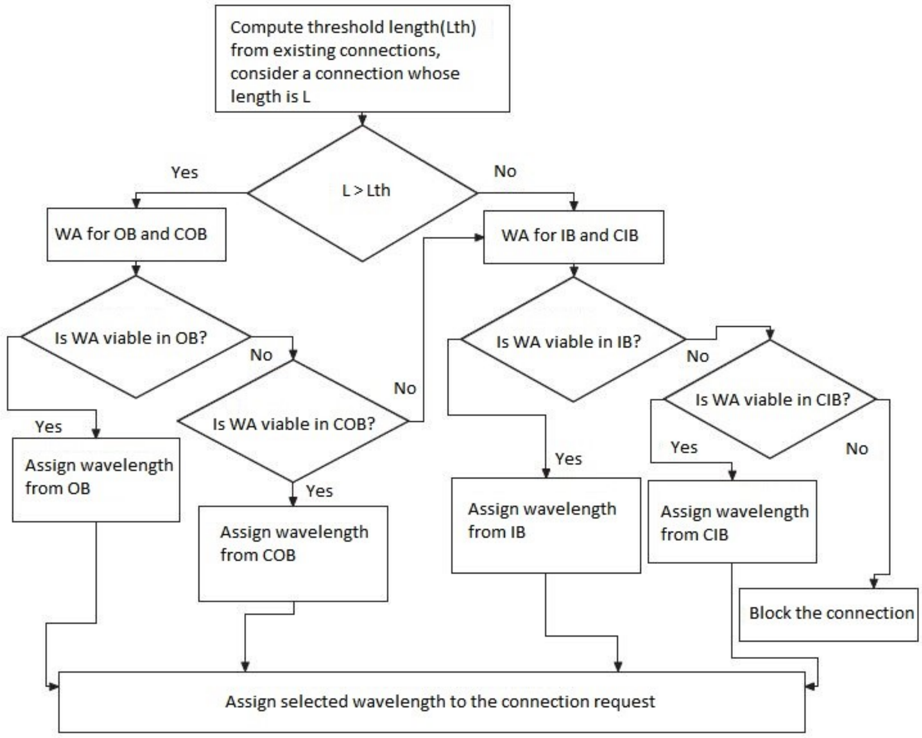
(c) Eight bands CIOBWA technique

Figure 3.3: Band division of transmission window in MOBWA, four bands CIOBWA and eight bands CIOBWA

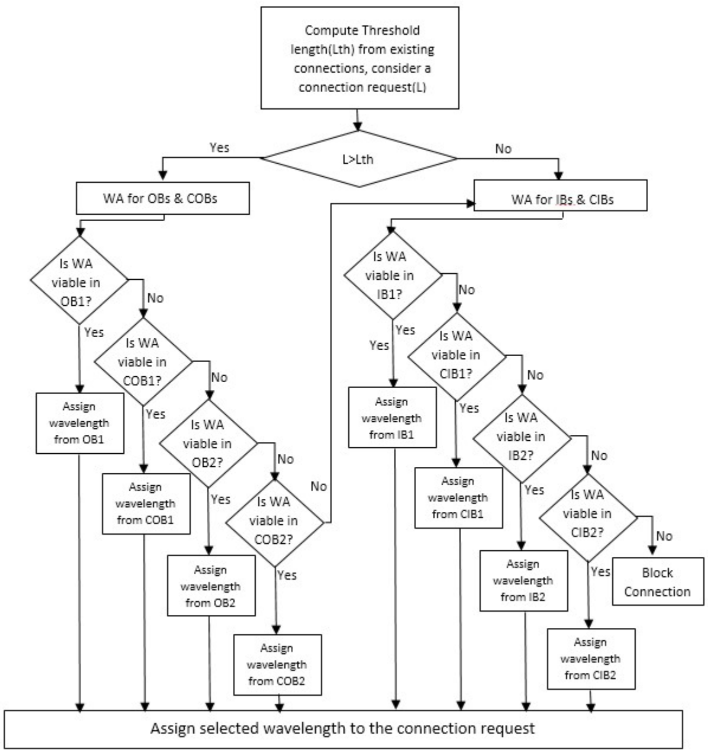
L_{th} decides whether the distance of given connection request is shorter or longer so as to be included in IB/CIB or OB/COB.

$$L_{th} = \frac{\sum_{\forall s\text{-}d\, pairs} Connection\, lengths}{Number\, of\, connections} \tag{3.21}$$

The flowchart of wavelength assignment in four bands and eight bands CIOBWA is presented in Figure 3.4. Flow chart of quality aware RWA used in this work is presented in Figure 3.5.



(a) Four bands CIOBWA technique



(b) Eight bands CIOBWA technique

Figure 3.4: Flow charts of WA in four bands CIOBWA and eight bands CIOBWA

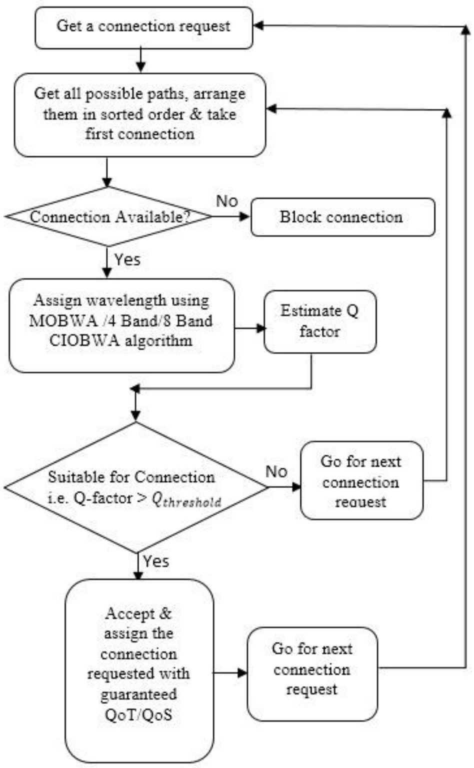


Figure 3.5: Modified routing and wavelength assignment flowchart

Chapter 4

Results and Discussions

4.1 Introduction

This section tells about the (1) blocking probability at different wavelength values, (2) guaranteed connections calculation, and (3) blocking probability at various wavelengths and connection requests (loads). There are some assumptions considered: (1) in the considered topology all nodes are of same type, (2) links have equal number of wavelengths, (3) shot noise and thermal noise are considered to be absent, (4) all links follow wavelength constraint, and (5) any source–destination pairs have no connections prior to study.

4.2 Network topology

We consider following Network topology of 16 links and 10 nodes for demonstration of our proposed algorithm as shown in Figure 4.1 with following connection table.

Here central wavelength of 1500 nm, the quantum efficiency of 90% and responsivity η of 1.13 A/W are assumed. Other values considered are: β is FM index, β=FM index at $f_{RF} = 0.6$, $V_{LO} = 100$ and $V_{\pi} = 50$, $D_{PMD} = 0.5$, $\sigma = 0.1$ and IM Index, *m* in the range 0.1 to 0.4 [7].

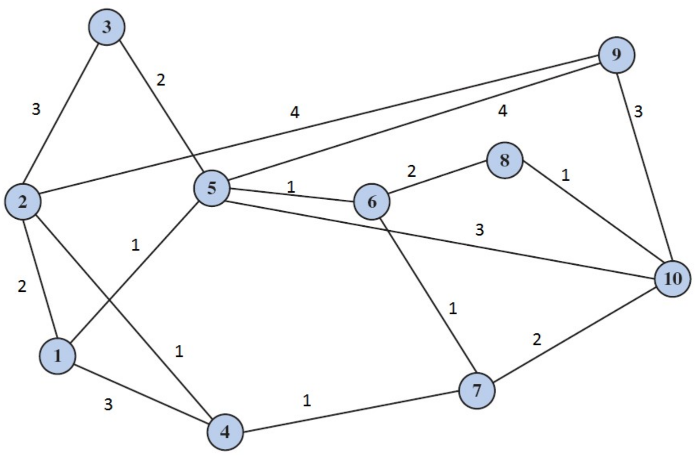


Figure 4.1: NSFNet topology used for simulation; length of link = number on link x 70 Km

No. of links	Source node	Destination node	Distance(in Kms)
1	1	2	140
2	1	4	210
3	1	5	70
4	2	3	210
5	2	4	70
6	2	9	280
7	3	5	140
8	4	7	70
9	5	6	70
10	5	9	280
11	5	10	210
12	6	7	70
13	6	8	140
14	7	10	140
15	8	10	70
16	9	10	210

Table 4.1: Connection Table

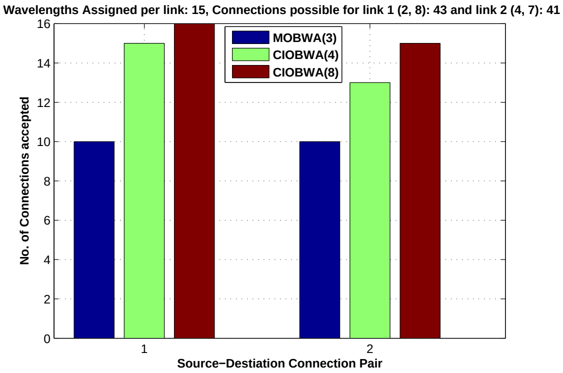
4.3 Analytical Results and Discussions

Simulation results of connections accepted versus source-destination (s, d) pairs using MOBWA, fours bands/ eight bands CIOBWA with assigned wavelength as 15, 20, 25 and 30, for two source destination node pairs i.e. (2, 8) and (4, 7), are given in Figure 4.2. The number of connections for link 1 i.e (2, 8) is 43 and for link 2 i.e. (4, 7) is 41.

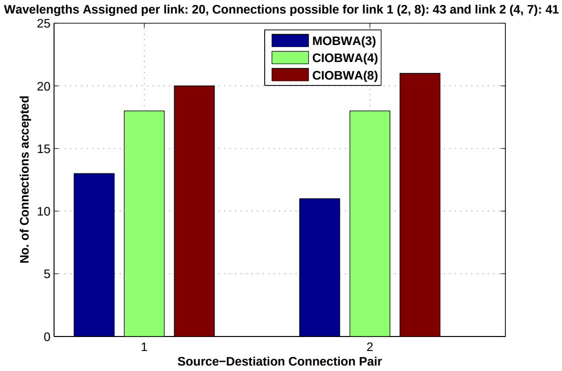
Simulation results of connections accepted at different WA techniques at different number of wavelengths assigned for three links i.e. (2, 8), (4, 7) and (3, 6) is presented in Figure 4.3. The number of connections for link 1 i.e (2, 8) is 43, for link 2 i.e. (4, 7) is 41 and for link 3 i.e. (3, 6) is 47. Likewise, simulation results of connections accepted at different WA techniques at different number of assigned wavelengths for four links i.e. (2, 8), (4, 9), (3, 6) and (1, 7) is presented in Figure 4.4.

Observation from graph validates that the connections accepted is higher in eight bands CIOBWA algorithm than that obtained using four bands CIOBWA algorithm and the number of connections accepted for four bands CIOBWA is still greater than MOBWA. It can also be deduced that assigning more number of wavelengths increases the number of accepted connections .

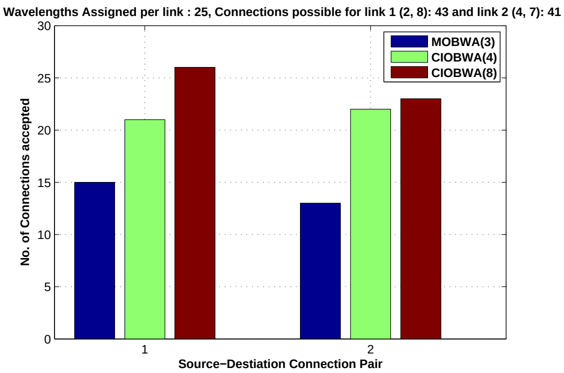
Simulation results of blocking probability (%) using MOBWA, fours bands/ eight bands CIOBWA with assigned wavelength being 15, 20, 25 and 30 considering (2, 8) and (4, 9) as



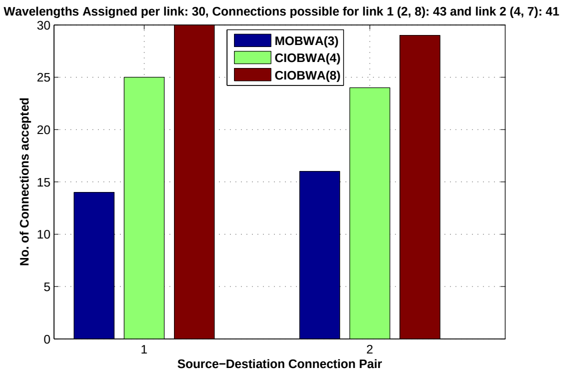
(a) Allotted number of wavelengths: 15



(b) Allotted number of wavelengths: 20



(c) Allotted number of wavelengths: 25



(d) Allotted number of wavelengths: 30

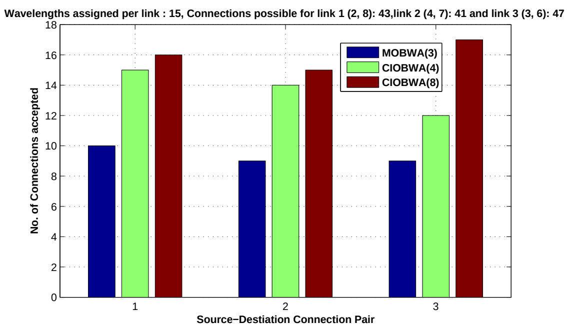
Figure 4.2: Number of accepted connections vs (s, d) connection pair for two links at different number of assigned wavelengths: (a) 15, (b) 20,(c) 25, (d) 30

source destination (s, d) pairs, are presented in Figure 4.5. Similarly results for three links (2, 8), (4, 9) and (3, 6) is shown in Figure 4.6. Results for four links (2, 8), (4, 9), (3, 6) and (1, 7) are presented in Figure 4.7.

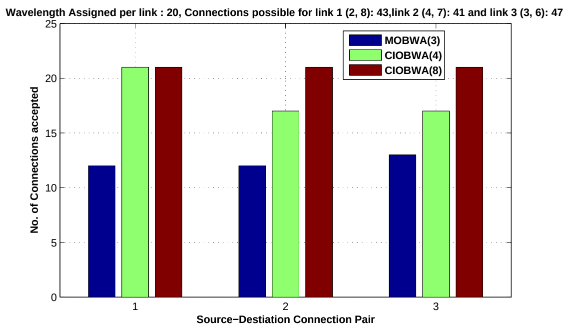
Observation from graph validates that the blocking probability is higher in MOBWA algorithm than blocking probability using four bands CIOBWA algorithm and blocking probability of four bands CIOBWA is still greater than eight bands CIOBWA. It can also be deduced that assigning more number of wavelengths decreases the blocking probability.

Similarly effects of using different WA mechanisms at different wavelengths on blocking probability considering different number of (s, d) pairs is shown in Figure 4.8.

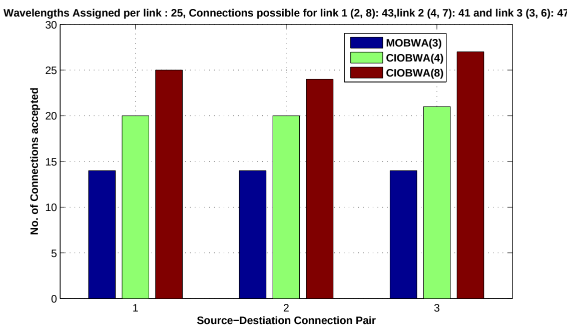
The graphs validate that, with a different number of wavelengths used per connection, blocking probability (%) is mostly lower for eight bands CIOBWA than using four bands CIOBWA and also than using MOBWA.



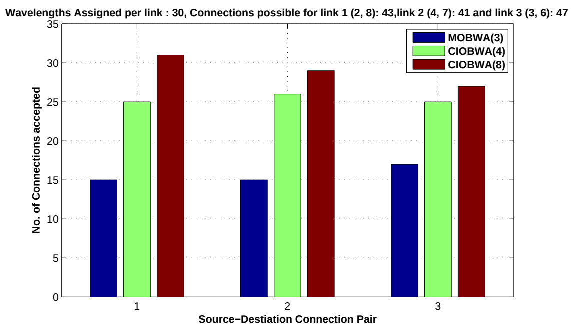
(a) Allotted number of wavelengths: 15



(b) Allotted number of wavelengths: 20

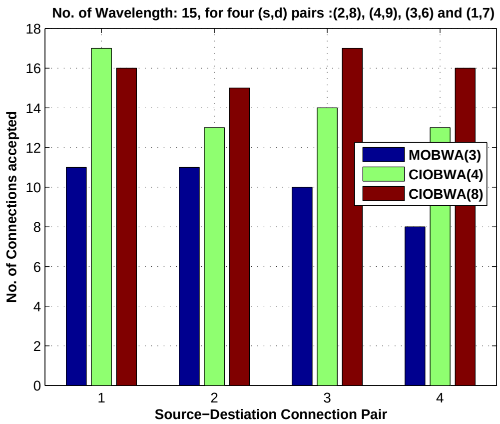


(c) Allotted number of wavelengths: 25

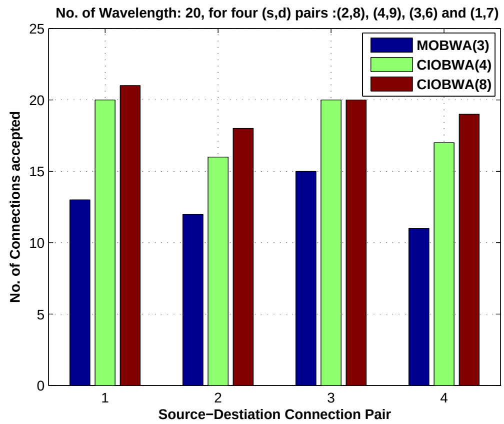


(d) Allotted number of wavelengths: 30

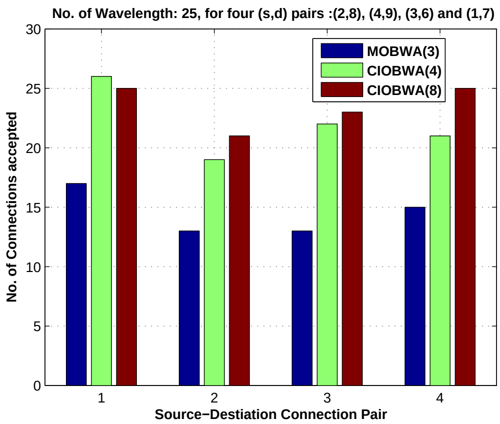
Figure 4.3: Number of accepted connections vs (s, d) connection pair for three links at different number of assigned wavelengths: (a) 15, (b) 20,(c) 25, (d) 30



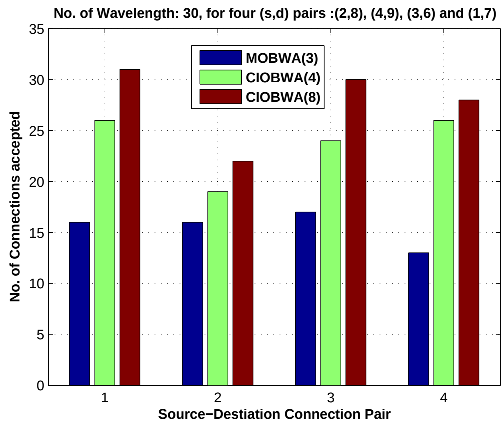
(a) Allotted number of wavelengths: 15



(b) Allotted number of wavelengths: 20

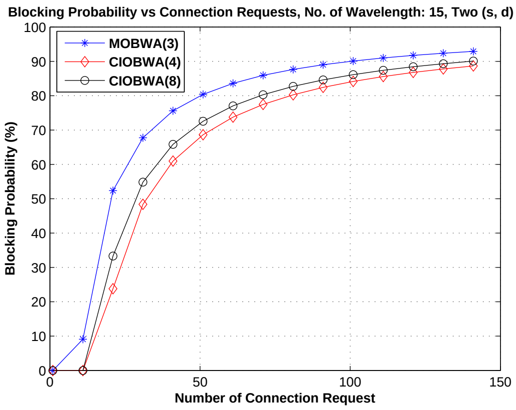


(c) Allotted number of wavelengths: 25

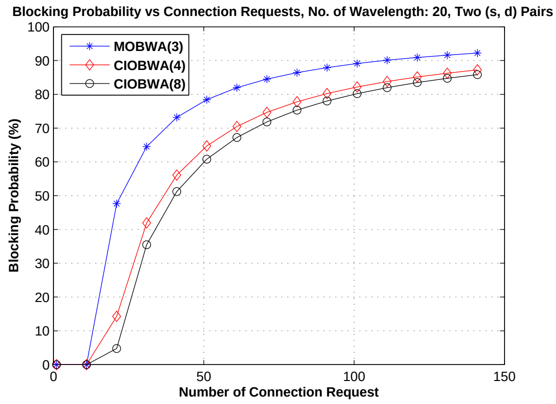


(d) Allotted number of wavelengths: 30

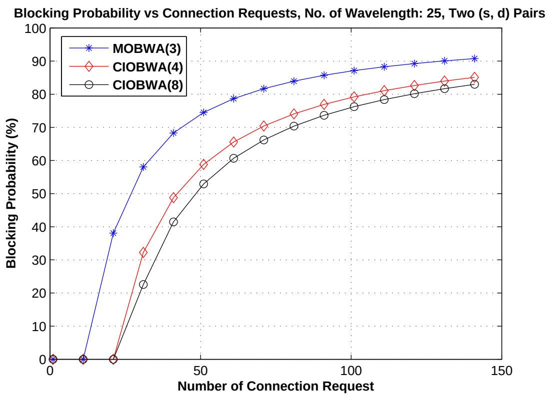
Figure 4.4: Number of accepted connections vs (s, d) connection pair for four links at different number of assigned wavelengths: (a) 15, (b) 20,(c) 25, (d) 30



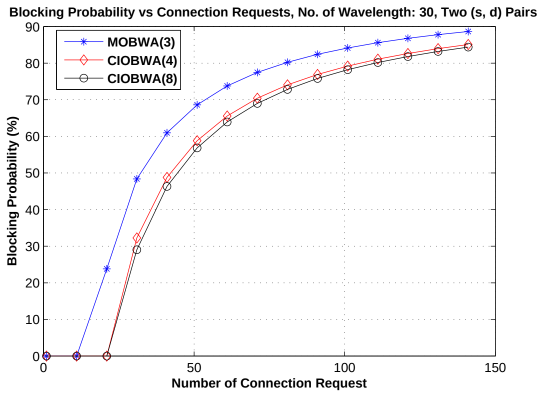
(a) Allotted number of wavelengths: 15



(b) Allotted number of wavelengths: 20

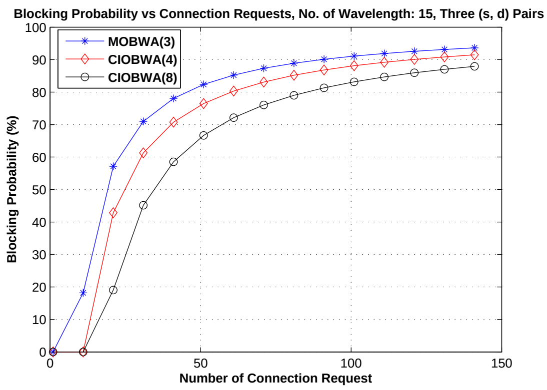


(c) Allotted number of wavelengths: 25

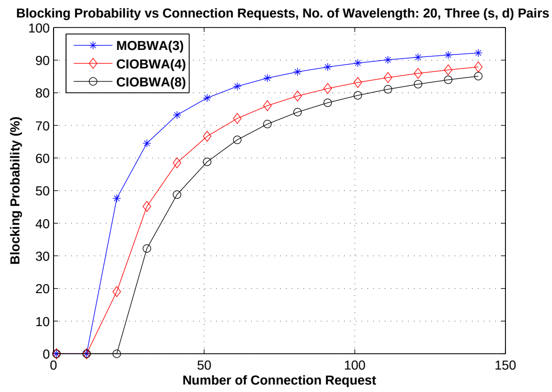


(d) Allotted number of wavelengths: 30

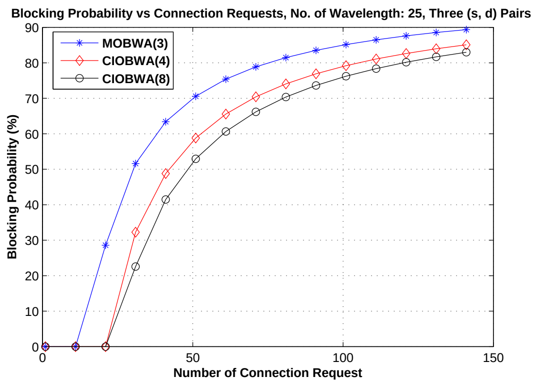
Figure 4.5: Blocking probability (in %) vs connections requested for two links: (2, 8) and (4, 9), at different number of assigned wavelengths : (a) 15, (b) 20,(c) 25, (d) 30



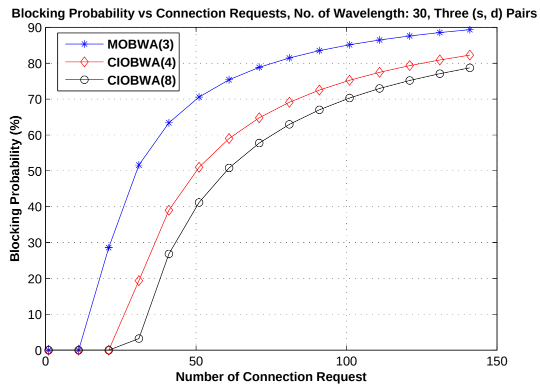
(a) Allotted number of wavelengths: 15



(b) Allotted number of wavelengths: 20

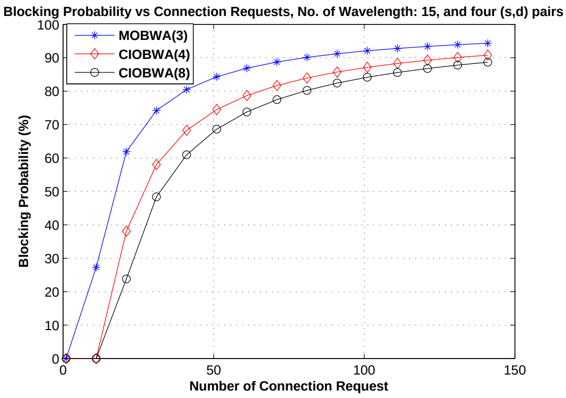


(c) Allotted number of wavelengths: 25

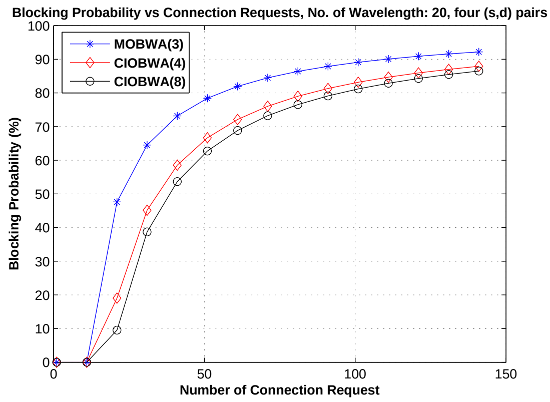


(d) Allotted number of wavelengths: 30

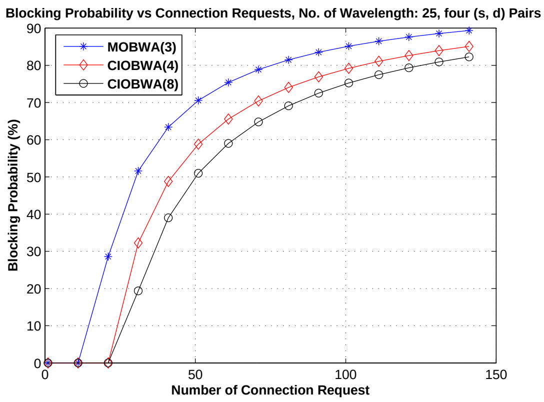
Figure 4.6: Blocking probability (in %) vs connections requested for three links: (2, 8), (4, 9) and (3, 6) at different number of assigned wavelengths : (a) 15, (b) 20,(c) 25, (d) 30



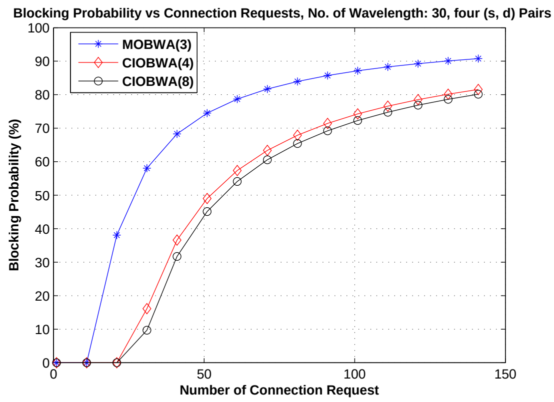
(a) Allotted number of wavelengths: 15



(b) Allotted number of wavelengths: 20

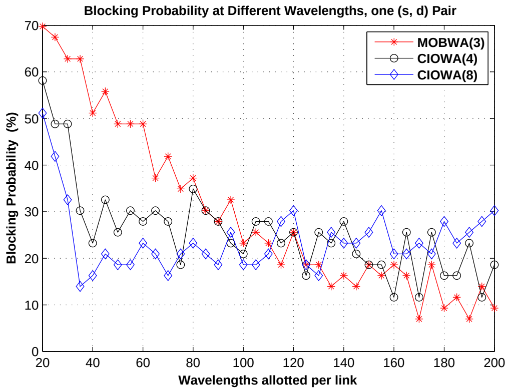


(c) Allotted number of wavelengths: 25

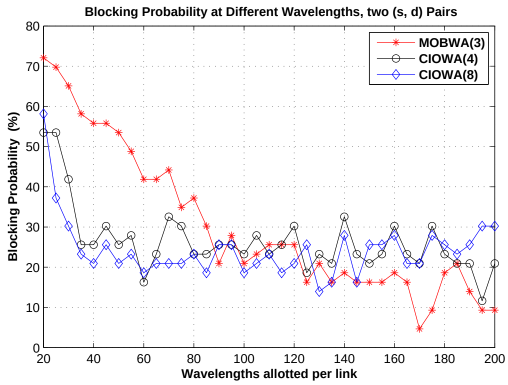


(d) Allotted number of wavelengths: 30

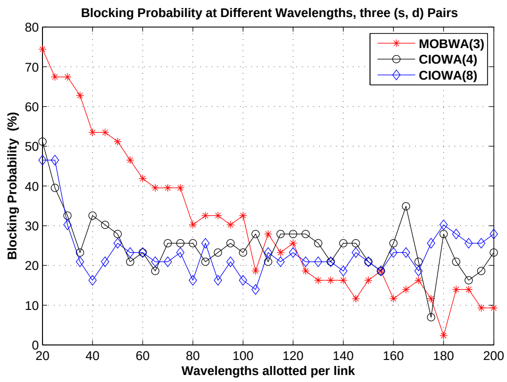
Figure 4.7: Blocking probability (in %) vs connections requested for four links: (2, 8), (4, 9), (3, 6) and (1, 7) at different number of assigned wavelengths : (a) 15, (b) 20,(c) 25, (d) 30



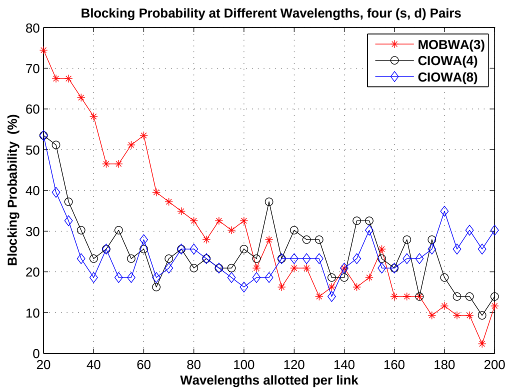
(a) single link: (2, 8)



(b) double link: (2, 8) and (4, 9)



(c) triple links: (2, 8), (4, 9) and (3, 6)



(d) quadruple links: (2, 8), (4, 9), (3, 6) and (1, 7)

Figure 4.8: Blocking Probability (%) vs number of wavelengths allotted per link: (a) single link, (b) double link, (c) triple link and (d) quadruple link

Chapter 5
Conclusion

5.1 Contributions

In this thesis, a system model for phase modulated radio over fiber WDM/ DWDM networks is derived, which analyses the connection quality based on the bit-error probability. This work analyses the optical connection quality with phase modulation as an important impairment parameter. It also analyses various wavelength assignment techniques such as conventional MOBWA and four bands /eight bands CIOBWA. This work analyses accepted connections for a given connection requests and blocking probability at different wavelengths and loads. It is observed that four bands /eight bands CIOBWA increases number of connections accepted than conventional wavelength assignment techniques, there by reducing blocking probability. Effects of impairments can be seen clearly through the graphs and be used as a basis for future works in this field.

5.2 Limitations

In this work following assumptions are considered:

- The topology has all nodes are of same type.
- Links have equal number of wavelengths.
- Shot noise and thermal noise are not taken into account.
- All links follow wavelength constraints in optical network.
- Any source–destination pairs have no connections prior to study.

There are many limitations of this work owing to the assumptions considered:

- Practical implementation of this work was not done. Real time noises like shot and thermal noise and other realistic leakages and conditioning are not included.
- The work has been done in MATLAB and includes no result using optical fiber commercial software like Optisim.

- The analysis done is a general one, without considering any realistic application.
- Path restoration during connection failures are not considered.
- All the nodes in a practical optical network may not be of same type.

5.3 Future works

A profound analysis of the proposed system is to be studied using optical simulators like Optisystem and the same has to be implemented in a real time optical network scenario. A path restoration algorithm is to be designed to deal with connection failure. More efficient optimization techniques are to be designed to optimize the quality of service that would deal with phase modulated RoF in WDM/DWDM networks. Specific application based survey and design is to be done in future. This work can be extended to different linear and non-linear impairments in RoF in WDM/DWDM networks.

References

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